Research Article

Integrated Assessment of Oil Palm Sludge as a Climate-Smart Feed Resource for Cattle Production in the Ecuadorian Amazon

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Abstract | The use of agro-industrial by-products represents a climate-smart strategy for sustainable livestock production in the Ecuadorian Amazon. Moreover, it constitutes a pivotal link between technological innovation and environmental sustainability. This study characterized the chemical composition and nutritional value of oil palm sludge for its potential use as a feed resource for ruminants. 16 samples were collected quarterly over one year from oil palm processing plants located in the provinces of Orellana and Sucumbíos, Ecuador. Chemical analyses were performed according to AOAC standard methods, nutritional evaluation was conducted using INRA feed evaluation system, and methane emission potential was estimated following the IPCC methodology. On average, oil palm sludge contained 24% dry matter, 79% organic matter, 16% crude protein, 12% ether extract, 65% neutral detergent fibre, and 34% acid detergent fibre. In vitro dry matter and organic matter digestibility averaged 38% and 27%, respectively, while gross energy and metabolizable energy reached 4.21 and 2.70 Mcal/kg^{-1} DM, respectively. No significant differences were detected between provinces or sampling periods ($P > 0.05$). These findings demonstrate that oil palm sludge is a promising alternative feed resource capable of partially replacing conventional feeds while simultaneously reducing agro-industrial waste accumulation. Its utilization could contribute to the development of more sustainable, circular, and climate-resilient livestock production systems in tropical ecosystems.

Keywords | Climate-smart livestock, Circular bioeconomy, Agro-industrial by-products, palm sludge, Ruminant nutrition.

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INTRODUCTION

According to FAO (2022), the global population is expected to reach 9.8 billion by 2050, highlighting the urgent need to ensure global food security while safeguarding human health and reducing the carbon footprint (Porqueddu *et al*., 2016; Varma *et al*., 2024). Consequently, one of the major challenges facing the livestock sector is to increase the production of animal-derived protein to meet the growing global demand while simultaneously transitioning toward more environmentally resilient production systems (González-Quintero *et al*., 2021; Rotz *et al*., 2019; Stanley *et al*., 2018). Worldwide, livestock and agricultural activities generate substantial quantities of by-products and waste, whose management poses significant economic and environmental challenges

(Guerrero *et al*., 2022).

Oil palm (*Elaeis guineensis*) is native to the tropical rainforests of West Africa, particularly the regions of Congo, Nigeria, and Ghana (Guerra, 2000). Over time, it has become one of the world's leading sources of vegetable oil (Utomo and Widjaja, 2018). The global expansion of oil palm cultivation began during the twentieth century, with large-scale plantations being established across Asia and Latin America in the 1960s, where tropical climatic conditions proved highly favorable for its growth (Lozano, 2024). In the northern Ecuadorian Amazon, oil palm cultivation has expanded rapidly over the past two decades, driven by the establishment of multinational companies and government incentives that played a key role in promoting plantation expansion (Hanum, 2020). Initially, production was primarily intended for the manufacture of edible fats, margarine, and soap (Cortes, 2009). During the last decade, oil palm production in Ecuador has increased exponentially in response to growing international demand, supported by substantial capital investments (Camacho et al., 2022). According to INEC- ESPAC (2025), the provinces of Orellana and Sucumbíos currently comprise 50,556 hectares of oil palm plantations, making oil palm the second most extensive crop in the Ecuadorian Amazon after cacao. Consequently, the oil palm industry generates large volumes of sludge, an agro-industrial by-product with considerable environmental implications if not properly managed. Despite its widespread availability and continuous production in the region, limited research has been conducted to evaluate oil palm sludge as an alternative feed resource for ruminants (Varas, 2015).

In Ecuador, ruminant production systems rely primarily on forage-based diets composed of grasses and legumes (Guamán-Rivera *et al*., 2023). In the Ecuadorian Amazon, dual-purpose cattle production systems predominate (Peralta *et al*., 2024), although they are generally characterized by low productivity. Previous studies have documented the rapid expansion of agricultural crops such as oil palm, rice, coffee, and cacao throughout the region. However, limited attention has been given to the potential utilization of the agro-industrial by-products generated from these production systems as alternative feed resources for ruminants. Their valorization could reduce biomass waste while contributing to climate change mitigation through the implementation of circular and resource-efficient livestock production systems (Ríos et al., 2023).

Given that the availability of forage resources for livestock production in Ecuador is insufficient during prolonged dry periods, resulting in significant declines in milk and meat production (Guamán-Rivera *et al*., 2024; Guerrero-Pincay *et al*., 2023), the utilization of oil palm sludge as a dietary supplement for ruminants could represent an effective strategy within a circular bioeconomy framework. By converting this agro-industrial by-product into a value-added feed resource, the integration of oil palm production and livestock systems could be strengthened, thereby closing nutrient and resource loops. Furthermore, this approach contributes directly to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) by supporting sustainable livestock production, SDG 12 (Responsible Consumption and Production) through the valorisation of agro-industrial by-products, and SDG 13 (Climate Action) by promoting climate-smart livestock systems with the potential to mitigate greenhouse gas emissions (Gil, 2018). Within this context, the present study aimed to characterize the nutritional composition of oil palm sludge collected from the major palm oil extraction mills located in the northern Ecuadorian Amazon, specifically in the provinces of Orellana and Sucumbíos.

MATERIALS AND METHODS

Study area

The study was conducted in the province of Orellana, located in northeastern Ecuador within the Ecuadorian Amazon Region, which is characterized by a humid tropical climate. Average temperatures range from 18 to 32°C, and the province has a mean elevation of approximately 275 m above sea level (m a.s.l.). In contrast, the province of Sucumbíos also exhibits a humid tropical climate, with an average annual temperature of 28°C and an elevation ranging from 800 to 3,200 m a.s.l.

Collection of palm sludge and preparation of samples for analysis

From the palm oil mills in Orellana and Sucumbíos, palm sludge samples (1 kg on average) were collected every three months (16 total) and transported in cool boxes at an average temperature of 4°C in properly labelled plastic bags. Once at the specialist science laboratory of the Chimborazo Higher Polytechnic School, Orellana campus, Ecuador, 100 g of the material was weighed in duplicate onto aluminium trays and placed in a forced-air oven (80110 REV D, Spain) for 48 hours at temperatures of 60 and 103°C. The samples dried at 60°C were then ground to a particle size of 1 mm using a Thomas Wiley mill (Arthur H. Thomas, Philadelphia, PA, USA) in accordance with the AOAC (2000) methodology.

Chemical analysis

All analyses were carried out in accordance with the standard AOAC (2000). Consequently, the ash content was determined in a muffle furnace at 550°C for 6 hours; following this, the percentage of organic matter (OM) was calculated as 100 – % ash, ether extract (AOAC, 1990; No. 920.39), acid detergent fibre (AOAC, 1990; No. 973.18) and neutral detergent fibre using heat-stable amylase and sodium sulphite according to Van Soest *et al*. (1991). Meanwhile, crude protein content was determined using the micro-Kjeldahl method (#979.09).

The in vitro digestibility of palm sludge was determined in a Daisy II incubator (Ankom Technology) in accordance with the methodology of Aufrere and Michalet-Doreau (1988) and Van Soest *et al*. (1991), using artificial saliva previously prepared with dibasic sodium phosphate (216 g) and sodium bicarbonate (58.8 g). Similarly, 2 kg of solid-liquid ruminal content was collected from 3-year-old cattle managed under a 100% pasture-based production system, receiving no concentrate or nutritional supplementation, 15 minutes after slaughter and transported in a cooler at 39°C. Once in the laboratory, the ruminal fluid was collected in a beaker preheated with water at 39°C, with CO_2 gas being added continuously. Following these procedures, 1200 mL of artificial saliva and 800 mL of ruminal fluid were mixed in the Daisy II vials. The F57 bags, containing 0.3000 g of sample, were then heat-sealed, placed in the apparatus for a period of 48 hours, and CO_2 was applied after 24 hours. After this time, the bags were removed and washed with distilled water, then dried in an oven at 65°C for 48 hours.

Energy values

The chemical composition obtained made it possible to estimate the energy values of palm sludge for the two provinces (Orellana and Sucumbíos). To this end, using the formulae from INRA (2018) and those developed by Guamán-Rivera *et al*. (2023), expressed in kcal/kg of dry matter, the following were determined: gross energy (GE), digestible energy (DE), metabolizable energy (ME) and net lactation energy. Finally, in order to estimate the amount of methane, the IPCC (2006; Methane (MJ/day)=0.065×GE intake (MJ/day) (Patra, 2017).

Statistical analysis

Data were analyzed using the MIXED procedure of SAS v.9.4 (SAS Institute Inc., Cary, NC, USA). Before analysis, data were tested for normality using the UNIVARIATE procedure. The statistical model included processing plant (or location, according to the experimental design) and sampling period (quarterly) as fixed effects, while the experimental unit corresponded to each independent palm sludge sample collected from each processing plant. Least-squares means were compared using Tukey's adjustment, and statistical significance was declared at $P < 0.05$.

RESULTS

The chemical composition data for the palm sludge are shown in Table 1. The dry matter (DM) content ranged from 29 to 21% indicating little variability (average 24 %; coefficient of variation 9 %). Ash content averaged 20 %; furthermore, based on the coefficient of variation (23 %), this shows significant variability, in line with the mean value obtained for organic matter (79 %, on average). Regarding to crude protein (CP), maximum values of 16% were observed, which may be influenced by the type of management, fertilisation levels and rainfall. For crude fibre, the descriptive statistics show average values of 62%, with maximums of 85% and minimums of 45%. The in vitro digestibility of DM and OM averaged 38% and 27%, respectively.

Chemical composition

The composition data are shown in Table 2. When comparing the extraction plants, the dry matter contents did not differ according to location (Sucumbíos vs. Orellana) or according to the year of assessment. It is interesting to note that high ash contents were observed in palm sludge, regardless of location (20.94 ± 4.3; P = 0.64) or quarter (P = 0.27). With regard to organic matter content, although numerically lower levels were observed in palm sludge from Orellana (80.6 vs. 78.35 ± 5.06%; P = 0.5) and variations were noted across the year (ranging from 77.84 to 83.51 %), these were not statistically significant. As for the crude protein content of the palm sludge analysed, the values were above the minimum threshold for ruminants (> 7%, on a dry matter basis), but variations were observed over the course of the year, which may have been influenced by factors such as rainfall patterns and fertilization levels. Furthermore, given that palm sludge, as an agro-industrial by-product, could be considered as a supplement for ruminants, the values for structural fibres NDF (65.9 ± 1.91 per cent) and ADF (34.2 ± 2.75 per cent) are higher than those considered ideal for ruminant feed. For this reason, its inclusion in diets for ruminants should be monitored to ensure it does not limit voluntary dry matter intake.

The nutritional values of palm sludge, calculated using INRA formulas, are shown in Table 3. The IVDMD showed no variation by location (38.7 ± 8.6%; P = 0.76) or over the course of the study year (P = 0.9). Similarly, this is reported for the IVDOM (27.8 ± 13%; P = 0.69 to 0.82; Table 3). These results can be partly explained by the high fibre content (Table 2), which is reinforced by the negative correlations observed with the NFD (r = −0.59 to 0.62; P = 0.03 to 0.04) and ADF (r = −0.59 to 0.62; P = 0.02 to 0.03). Gross energy values did not differ according to location (P = 0.97) or time of year (0.68); furthermore, no significant differences were observed in the CH_4 values obtained in this study (0.26 ± 0.01 MJ/day; P = 0.18 to 0.35).

Table 1: Descriptive statistics on the chemical composition and in vitro digestibility of palm sludge.

Item	Descriptive statistics				
	Mean	Standard deviation	Maximum	Minimum	Coefficient of variation
Chemical composition, % on dry matter basis					
Dry matter	24	2.4	29	21	9
Organic matter	79	4.6	84	72	5
Crude protein	13	1.41	16	11	10
Ether extract	12	3.04	21	9	25
Ash	20	4.7	27	15	23
Nitrogen-free extract	20	8.8	31	5	44
Crude fibre	62	17.5	98	45	28
Neutral detergent fibre	68	6	72	55	8
Acid detergent fibre	35	7	40	32	15
IVDMD, %	38	6.1	48	28	16
IVDOM, %	27	9.6	41	10	35
g/kg DM					
Crude protein	132	14	161	114	10
Etheric extract	120	30	211	95	25
Organic matter	791	46	841	725	5

Table 2: Least squares means for the chemical composition of palm sludge by extraction plant in northern ecuador.

Item	Extractor		Quarter					P = value		
Chemical composition, % % on dry matter basis	**Sucumbíos**	**Orellana**	**I**	**II**	**III**	**IV**	**SEM**	**Extractor**	**Quarter**	**E × Q**
Dry matter, %	24.72	24.66	24.26	22.89	24.9	26.37	2.5	0.97	0.7	0.95
Ash, %	21.59	20.29	20.61	21.12	16.6	25.43	4.3	0.64	0.27	0.47
Organic matter, %	80.6	78.35	83.51	77.84	76	80.56	5.06	0.5	0.43	0.76
Crude fibre, %	48.14	69.87	56.24	63.12	60.4	56.24	1.1	0.16	0.97	0.94
Crude protein, %	12.71	13.44	13.23	12.85	13	13.23	1.81	0.54	0.99	0.66
Nitrogen-free extracts, %	26.24	16.95	20.24	26.81	25.3	14.04	5.4	0.04	0.15	0.3
Neutral detergent fibre, %	67.3	64.5	62.5	66.5	70.1	63.2	3.91	0.17	0.97	0.64
Acid detergent fibre, %	34.6	33.8	36.5	37.8	34.3	35.9	2.75	0.17	0.97	0.95

SEM, standard error of the mean

Table 3: Nutritional values of palm sludge according to its origin in the northern amazon region of ecuador.

Item	Extractor		Quarter					P = value		
Nutritional values % on dry matter basis	**Sucumbíos**	**Orellana**	**I**	**II**	**III**	**IV**	**SEM**	**Extractor**	**Quarter**	**E × Q**
IVDMD, %	39.58	37.87	41.79	38.94	36.74	37.43	8.6	0.76	0.9	0.77
IVDOM, %	29.55	26.08	33.86	27.23	22.91	27.26	13	0.69	0.82	0.84
Gross energy, Mcal kg^{-1}	4.3	4.12	4.29	4.04	4.02	4.5	0.22	0.27	0.18	0.35
NEL, Mcal kg^{-1}	2.7	2.7	2.74	2.72	2.69	2.64	0.1	0.97	0.68	0.6
CH_4 enteric, MJ/day[1]	0.27	0.26	0.27	0.26	0.26	0.29	0.01	0.27	0.18	0.35

SEM, standard error of the mean; CH_4 enteric, IPCC (2006; Methane (MJ/day) = 0.065×GE intake; NEL, net energy for Lactation; [1] value calculated based on dry matter intake.

DISCUSSION

Today, the oil palm industry represents one of the fastest-growing industrial and economic sectors worldwide (Nasir *et al*., 2012). However, the large volume of by-products generated by this industry has prompted increasing interest in their valorization within the frameworks of climate change mitigation and the circular bioeconomy (Biglari *et al*., 2019; Thornton and Gerber, 2010), in alignment with the United Nations Sustainable Development Goals (SDGs) (Gil, 2018). Consequently, oil palm by-products are increasingly being incorporated into livestock production systems as alternative feed resources. This approach is consistent with the principles of regenerative livestock farming, which seeks to reduce dependence on conventional concentrate feeds associated with a high carbon footprint (Don *et al*., 2023; Martínez-Salinas *et al*., 2024). Furthermore, as reported by Hanum (2020), one of the main advantages of incorporating oil palm sludge into livestock diets is its high energy content. In addition, its favorable physicochemical characteristics and pleasant aroma enhance feed palatability, promoting voluntary intake by animals (Utomo and Widjaja, 2018; Abubakr *et al*., 2014; Badarina *et al*., 2023; Trisna and Rizal, 2020).

Reference values reported by Abubakr *et al*. (2014) and Badarina *et al*. (2023) indicate that oil palm sludge contains approximately 11–13% crude protein, 12–17% lipids, and 32.07% crude fibre, highlighting its potential as a partial substitute for conventional ingredients in ruminant diets. In this regard, Ciptaan *et al*. (2020) reported that the proportional replacement of a conventional energy source such as maize with oil palm sludge improved feed efficiency and growth performance in livestock species. Likewise, Malacatus-Cobos *et al*. (2023) demonstrated that including up to 20% oil palm sludge in ruminant diets can be economically advantageous while maintaining acceptable growth rates. Nevertheless, excessive dietary inclusion of oil palm sludge may reduce feed intake and nutrient digestibility because of its high crude fibre concentration (Abubakr *et al*., 2014). Oil palm processing by-products are characterized by elevated lignocellulosic and lignohemicellulosic fractions, which limit their digestibility (Lunsin, 2018). Therefore, these by-products should be incorporated into ruminant diets at appropriate inclusion levels to maximize their nutritional value without compromising animal performance (Bocanegra and Rochinotti., 2012). Also, the relatively low in vitro dry matter and organic matter digestibility observed in the present study is primarily associated with the high neutral detergent fibre and acid detergent fibre contents of oil palm sludge. Consequently, this by-product should not be considered as a complete replacement for conventional energy feeds but rather as a complementary ingredient included at appropriate dietary levels. From a practical standpoint, ration formulation should combine oil palm sludge with highly digestible forages or concentrate ingredients to ensure adequate nutrient supply, maintain voluntary feed intake, and optimize animal performance under tropical production systems.

Regarding methane emissions, expressed as MJ day^{-1}, Waghorn and Clark (2011) reported considerably higher values than those estimated in the present study when animals were fed high-quality pastures (16 vs. 0.26 MJ day^{-1}). Similarly, Patra (2017) reported methane production values exceeding 96%, corresponding to 7.96 ± 0.90 MJ day^{-1}, in tropical livestock production systems. These findings underscore the urgent need to develop and validate sustainable nutritional strategies capable of mitigating greenhouse gas emissions while remaining applicable under practical production conditions (Beauchemin *et al*., 2022; Guamán-Rivera *et al*., 2025).

Within the framework of Climate-Smart Livestock Systems (CSLS) (Delgado *et al*., 2019; Rose *et al*., 2021), multiple complementary approaches are integrated to simultaneously address food security (Edelman, 2014; Michalk *et al*., 2019), climate change mitigation (Joy *et al*., 2020; Thornton and Gerber, 2010), and the efficient utilization of agro-industrial residues. Climate-smart livestock systems emphasize sustainable animal production practices that promote the use of locally available forage resources and agro-industrial by-products as cost-effective feed alternatives while minimizing environmental impacts.

In the northern Ecuadorian Amazon, this approach is particularly relevant considering the low productivity of cattle production systems in terms of both milk and beef output (Guamán-Rivera *et al*., 2023, 2024, 2025). Furthermore, according to the typology proposed by Peralta *et al*. (2024), approximately 56% of livestock producers in the region operate under subsistence production systems. From an environmental perspective, the northern Ecuadorian Amazon is one of the world's most biologically diverse regions but is increasingly threatened by anthropogenic pressures associated with oil extraction Wasserstrom and Southgate (2013) and, more recently, illegal mining activities (Mestanza *et al*., 2023). Consequently, the valorization of agro-industrial by-products as alternative feed resources represents a strategic opportunity to reduce production costs, improve livestock productivity and farmers' livelihoods, while promoting environmentally sustainable production systems, consistent with the recommendations of the FAO (2018). A limitation of the present study is that methane emissions were estimated using the IPCC (2006) predictive equation based on gross energy intake rather than being directly measured through respiration chambers, the SF_6 tracer technique (Berndt *et al*., 2014a), or in vitro gas production systems. Therefore, the methane values reported should be interpreted as theoretical estimates. Future studies should directly quantify enteric methane emissions to validate these predictions under tropical production conditions.

CONCLUSION

Based on this research, it is evident that, due to its nutritional composition, palm sludge constitutes a potential resource as a strategy for climate-smart livestock systems in the northern Amazon region of Ecuador. Indeed, given its energy and protein content and as no differences were observed between provinces or seasons its composition appears to be relatively stable. Nevertheless, its inclusion in ruminant diets should be limited due to its high fibre content and low digestibility. In any case, the inclusion of agro-industrial by-products promotes the circular economy, whilst also reducing environmental impact.

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NOVELTY STATEMENT

This research presents the first integrated assessment of oil palm sludge from the Ecuadorian Amazon, combining chemical characterization, digestibility evaluation, feed energy prediction using the INRA system, and methane emission estimation within a climate-smart livestock framework. The study fills a critical knowledge gap regarding the valorization of oil palm agro-industrial residues in Latin American tropical ecosystems and demonstrates their potential to support circular bioeconomy approaches, reduce waste accumulation, and partially replace conventional feed resources in cattle production systems.

AUTHOR'S CONTRIBUTION

Conceptualization, Elsa Flor Ordoñez Bravo, Xavier Cristobal Quishpe Mendoza, Jorge Washington Armas Cajas, Marco Ramiro Usca Tiuquinga and Santiago Alexander Guamán Rivera Data collection. Elsa Flor Ordoñez Bravo, Xavier Cristobal Quishpe Mendoza, Jorge Washington Armas Cajas, Marco Ramiro Usca Tiuquinga prepared the manuscript for publication.

Generative AI and AI assisted technology statement

The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest

The authors have declared no conflict of interest

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